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Influence of a magnetic field on the Coulomb drag between quantum wires in the ballistic regime

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Abstract. The influence of a magnetic field H on the Coulomb drag between quantum wires is studied theoretically for low temperatures, when the electron motion along the wires is nearly ballistic. A considerable decrease of the drag transresistance is found as a result of the suppression of backscattering in electron-electron collisions at $H \sim 1$ T.

Introduction

The Coulomb drag in spatially separated low-dimensional electron systems has received a great deal of attention and has nearly developed into a separate field; a recent review is found in Ref. [1]. In particular, the drag between quantum wires was studied theoretically [2] assuming scattering of the carriers, e.g., by impurities. It is however, difficult to check experimentally these results in microstructural samples because the actual double-quantum-wire systems [3] are normally shorter than 1 μm and electron transport there is either ballistic or mesoscopic.

Recently, Gurevich *et. al.* [4], demonstrated the possibility of the drag effect in the regime in which most of the electrons travel through the wire ballistically. However, a few of the electrons experience backscattering due to the interaction with the electrons of the other wire, and this modifies the time-averaged distribution functions in such a way that the drag effect appears. Such a ballistic Coulomb drag (BCD) has not yet been observed experimentally. However, further theoretical studies of the BCD are important because they would bring new information and thereby stimulate experimental work in this new area. In this paper we investigate the effect of a magnetic field H applied perpendicular to the plane of the wires on the BCD. The backscattering processes, which are essential for the drag effect to appear, are suppressed by the magnetic field because the spatial overlap between the forward- and backward-propagating electron states decreases as the states tend to localize near the opposite edges of each wire. For this reason, we claim that the BCD will be suppressed and our aim is to study this suppression quantitatively.

Below we present the double-quantum-wire model and derive a general expression for the drag transresistance ρ_{D}. Then we give the numerical results for the magnetic-field dependence of ρ_{D} and a brief discussion.

1 General formalism

We use a model of a four-terminal double-quantum-wire system, similar to those investigated in the "directional coupler" problem [5]. Two closely spaced quantum wires (numbered 1 and 2) with parabolic confinement along the y direction are contacted independently to four leads at $x = -L/2$ and $x = L/2$, where L is the length of the wires. The leads have potentials $v_1(\pm L/2) = v_{1\pm}$, and $v_2(\pm L/2) = v_{2\pm}$. Applying the bias $v_{2-} - v_{2+}$ to the leads of wire 2 (drive wire) we obtain the current I flowing through wire 2; this current induces a voltage $v_{1-} - v_{1+}$ in wire 1 (drag wire). This is the typical setup for drag measurements [ ]. We assume that the barrier between the wires is high enough to allow the neglect of tunneling.

The wave functions $\Psi_{jnk}(x,y) = e^{ikx}\chi_{jnk}(y)$ (n is the Landau-level number, $j = 1, 2$, and k is the wave vector) of electrons, confined by the potentials $U_j = \varepsilon_j^0 + m\Omega_j^2(y - y_j)^2/2$ in the presence of a perpendicular magnetic field H, are given by $\chi_{jnk}(y) = (\pi^{1/2}\ell_j 2^n n!)^{-1/2}\, H_n((y - Y_j)/\ell_j)) \exp(-(y - Y_j)^2/2\ell_j^2)$. The corresponding spectrum $\varepsilon_{jn}(k)$ (spin splitting is neglected) reads

$$\varepsilon_{jn}(k) = \varepsilon_j^0 + \hbar\omega_j(n + 1/2) + (\hbar^2/2m_j)(k - y_j/\ell_c^2)^2, \tag{1}$$

Here $\omega_j^2 = \omega_c^2 + \Omega_j^2$, $\omega_c = eH/mc$ is the cyclotron frequency $m_j = m\omega_j^2/\Omega_j^2$, $\ell_c = \sqrt{\hbar/m\omega_c}$ is the magnetic length, $\ell_j^2 = \hbar/m\omega_j$, and $Y_j = [\Omega_j^2 y_j + \hbar\omega_c k/m]/\omega_j^2$ are the positions of the centers of the oscillators. Since we do not consider electron transitions between the wires, we will shift the wave vectors $k - y_1/\ell_c^2 \to k$ for wire 1 and $k - y_2/\ell_c^2 \to k$ for wire 2. Then the centers of the oscillators will read $Y_j = y_j + (\hbar\omega_c/m\omega_j^2)k$. We also assume that only the lowest Landau levels of both wells are populated ($n = 0$) and omit the index n.

If the distribution functions $f_{jk}(x) \equiv f_{jk}$ change over distances much longer than both the electronic wavelength π/k and the characteristic radius of the interaction potential, we can write the Boltzman kinetic equations as

$$\frac{\hbar k}{m_j}\frac{\partial f_{jk}(x)}{\partial x} = -\frac{4\pi}{\hbar}\sum_{j'k'q}\left|M_{kk'q}^{jj'j'j}\right|^2 \delta(\varepsilon_{jk} + \varepsilon_{j'k'} - \varepsilon_{j,k-q} - \varepsilon_{j',k'+q})$$
$$\times[f_{jk}(1 - f_{j,k-q})f_{j'k'}(1 - f_{j',k'+q}) - f_{j,k-q}(1 - f_{jk})f_{j',k'+q}(1 - f_{j'k'})]. \tag{2}$$

where the collision integrals account only for electron-electron scattering. The Coulomb matrix elements $M_{kk'q}^{jj'j'j}$ are given by

$$M_{kk'q}^{jj'j'j} = \frac{2e^2}{\kappa}\int dy \int dy' K_0(|q||y - y'|)\chi_{jk}(y)\chi_{j'k'}(y')\chi_{j'k'+q}(y')\chi_{jk-q}(y). \tag{3}$$

Here κ is the dielectric constant and K_0 is the modified Bessel function. In the one-dimensional case the intrawire ($j = j'$) part of the collision integral vanishes due to the restriction $q = k - k'$ following from the energy conservation law in Eq. (2). The exchange part (not written in Eq. (2)) vanishes for the same reasons.

It is convenient to write separately the distribution functions for the forward- and backward-moving electrons as $f_{j|k|}^{>} = f_{jk}|_{k>0}$ and $f_{j|k|}^{<} = f_{jk}|_{k<0}$, respectively. For these functions the boundary conditions are given in the Landauer-Buttiker approach by $f_{jk}^{>}(-L/2) = f(\varepsilon_{jk} - e\delta v_{j-})$ and $f_{jk}^{<}(L/2) = f(\varepsilon_{jk} - e\delta v_{j+})$, where $\delta v_{j\pm} = v_{j\pm} - v$, v is the equilibrium potential, $f(\varepsilon) = [e^{(\varepsilon - ev)/T} + 1]^{-1}$, and T is the temperature. For $j = 1$ and $j = 2$, Eq. (2) gives two coupled kinetic equations, whose solution allows to express the unknown potentials v_{1-} and v_{1+} through the fixed v_{2-} and v_{2+} values and thereby calculate the BCD.

2 Calculation of transresistance, results, and discussion

If most of the electrons move through the wires balistically, Eq. (2) can be solved by simple iterations. The zero-order approximation gives $f^{>}_{jk}(x) = f(\varepsilon_{jk} - e\delta v_{j-})$ and $f^{<}_{jk}(L/2) = f(\varepsilon_{jk} - e\delta v_{j+})$. Substitution of these functions in the collision integral gives non-zero contribution for the interwire collisions with backscattering. Taking into account that $v_{1-} - v_{1+}$ is considerably smaller than $v_{2-} - v_{2+}$ due to the assumed weak Coulomb coupling, we finally obtain, in the linear approximation

$$f^{>}_{1k}(x) = f(\varepsilon_{1k} - e\delta v_{1-}) + (m_1/\hbar k)\lambda_{>}(k)e(v_{2-} - v_{2+})(x + L/2), \tag{4}$$

$$f^{<}_{1k}(x) = f(\varepsilon_{1k} - e\delta v_{1+}) + (m_1/\hbar k)\lambda_{<}(k)e(v_{2-} - v_{2+})(x - L/2), \tag{5}$$

where $\lambda_{>}(k)$ and $\lambda_{<}(k)$ are determined by the Coulomb matrix elements and the equilibrium distribution functions only. The current flowing in the drag wire is given by $I_D = e/\pi \int dk(\hbar k/m_1)[f^{>}_{1k}(x) - f^{<}_{1k}(x)]$ (this current does not depend on x due to the property $\int dk[\lambda_{>}(k) - \lambda_{<}(k)] = 0$, which follows from detailed balance). The drag transresistance is given by $\rho_D = -(v_{1-} - v_{1+})/I$ and the ballistic current I by $I = (v_{2-} - v_{2+})/R_0$, where $R_0 = h/2e^2$ is the resistance quantum. From the requirement $I_D = 0$ we obtain

$$\rho_D = \frac{4e^2 m_0 L}{\hbar \kappa^2 T} \int_0^\infty dk \int_0^\infty dk' q^{-1}_{kk'} f(\varepsilon_{1k}) f(\varepsilon_{2k'})[1 - f(\varepsilon_{1k_1})][1 - f(\varepsilon_{2k_2})]$$
$$\times \left[\int\int \frac{dy dy'}{\pi \ell_1 \ell_2} K_0(q_{kk'}|y_1 - y_2 + y - y'|) Q_1(k, k_1, y) Q_2(-k', -k_2, y') \right]^2 . \tag{6}$$

Here $q_{kk'} = m_0(k/m_1 + k'/m_2)$, $k_1 = k' + \eta(k' - k)$, $k_2 = k + \eta(k' - k)$, $Q_j(p, p', y) = \exp\{-[(y - (\omega_c/\omega_j)\ell_j^2 p)^2 + (y + (\omega_c/\omega_j)\ell_j^2 p')^2]/2\ell_j^2\}$, $m_0 = 2m_1 m_2/(m_1 + m_2)$ and $\eta = (m_1 - m_2)/(m_1 + m_2)$.

Below we analyze in detail the case when the confining potentials are identical in both wires; this entails $m_1 = m_2$, $\ell_1 = \ell_2 = \ell$, $\Omega_1 = \Omega_2 = \Omega$, and $\omega_1 = \omega_2 = \omega$. We also assume that both the temperature T and splitting energy $\Delta = \varepsilon_1^0 - \varepsilon_1^0$ are small in comparison with the Fermi energy ε_F defined as $\varepsilon_F = ev - (\varepsilon_1^0 + \varepsilon_2^0)/2 - \hbar\omega/2$. These assumptions mean that the k and k' values contributing to the integrals are in narrow regions near $\sqrt{2m_0\varepsilon_F}/\hbar$, and the integrals over k and k' are calculated easily. We obtain

$$\rho_D = \frac{e^2 m^{3/2} \omega^3 L T}{2\sqrt{2}\pi \hbar^2 \kappa^2 \Omega^3 \varepsilon_F^{3/2}} \frac{(\Delta/2T)^2}{\sinh^2(\Delta/2T)} \exp\left(-\frac{8\omega_c^2 \varepsilon_F}{\hbar\omega\Omega^2}\right)$$
$$\times \left[\int_{-\infty}^{\infty} du e^{-u^2/2} K_0 \left(\sqrt{8\omega\varepsilon_F/\hbar\Omega^2}\, |w/\ell + u| \right) \right]^2 , \tag{7}$$

where $w = |y_1 - y_2|$ is the distance between the centers of the wires and u a dimensionless variable. Equation (7) demonstrates a significant suppression of the drag effect by the magnetic field, mostly due to the exponential factor and the increase, with H, of the argument of K_0. The decrease of ρ_D starts as $\rho_D(H) - \rho_D(0) \sim -H^2$ and becomes exponential with increasing H. The characteristic H for this suppression is determined by the Fermi energy and wire parameters. It is estimated as $H = (mc/e)\sqrt{\hbar\Omega^3/8\varepsilon_F}$ and is of the order of 1 T for typical wire parameters. Another less important factor, which contributes to the magnetic-field dependence of the BCD transresistance is the dependence

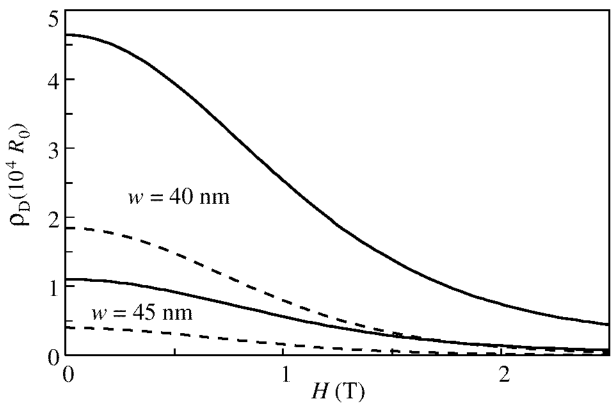

Fig. 1. Dependence of the transresistance ρ_D on the magnetic field H at two different Fermi energies $\varepsilon_F(0) = 3$ meV (solid) and $\varepsilon_F(0) = 4$ meV (dashed). The two upper curves correspond to $w = 40$ nm and the two lower ones to $w = 45$ nm.

of ε_F on H. It is taken below as $\varepsilon_F(H) - \varepsilon_F(0) = -\hbar(\omega - \Omega)/2$, under the assumption that v is constant.

In Fig. 1 we show the field dependence of ρ_D (in units of $h/2e^2$) for the resonance condition $\Delta = 0$ for which the drag is maximal [4]. The curves are plotted for two different values of $\varepsilon_F(0)$ and w shown in the caption. The other parameters used, common to all curves, are $\hbar\Omega = 5$ meV, $T = 1$ K, $m = 0.067$ of the free electron mass, $\kappa = 13$, and $L = 0.5$ μm. Although the variations of both ε_F and w considerably modify ρ_D, they do not influence the field dependence qualitatively.

In summary, we have theoretically demonstrated the magnetic-field induced suppression of the drag effect between two quantum wires in the ballistic transport regime. This suppression results from that of backscattering in the interwire Coulomb collision processes and is significant at $H \sim 1$ T. We hope that these results will stimulate further experimental investigations of electron transport in double-quantum-wire systems.

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